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DESIGN AND MECHANISM OF AN AUTOCATHODE

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16. Abstract

The design of a test device for an autocathode is described and a theoretical investigation of the autocathode mechanism is given. The autocathode is located in the center of a discharge chamber with a cylindrical anode in a 100-ℓ vacuum tank. The ignition of the autocathode requires special means and is also explained. The electron emission mechanism of this cathode was found as a field emission. Finally, the electrical field, the electron and ion current density was calculated in the cathode volume for a presupposed discharge current. Performance data are presented in tables and in diagrams.

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Notation

A_B	cm^2	Cryosurface of the refrigerating baffle
A_K	cm^2	Hg surface at cathode
C_p	cal/degree/mol	Molar heat
E	V/cm	Electrical field strength
e	Asec	Elementary electrical charge
F	mN, dyne	Thrust of thruster
I_g	A	Total current (ions + electrons)
I_i	A	Ion current
I_e	A	Electron current
j	A/cm^2	Total current density (ions + + electrons
j_{eF}	A/cm^2	Current density due to electron field emission
j_{eT}	A/cm^2	Current density due to thermal electron emission
j_i	A/cm^2	Ion current density
j_e	A/cm^2	Electron current density
k	erg/degree	Boltzmann constant
M_{Hg}		Atomic weight of mercury
m_{Hg}	g	Mass of mercury atom
m_e	g	Mass of electron
m_p	g	Mass of proton
m_i	g	Ion mass
m'_{Hg}	$g/sec/cm^2$	Evaporation rate of Hg
$\dot{m}$	g/sec	Mass throughput
$\dot{m}_F$	g/sec	Mass throughput, thruster
$\dot{m}_o$	g/sec	Neutral particle throughput
P_s	torr	Saturation vapor pressure
q_o	cal	Heat of evaporation
R	cal/degree/mol	Gas constant
r_K	cm	Free surface of Hg on the cathode
S_B	ℓ/sec	Pumping rate, refrigerating baffle
T	°K	Temperature

T_K	°C	Cathode temperature
U_K	V	Cathode potential fall
Ue	eV	Electron work function
v_a	cm/sec	Beam velocity
v_e	cm/sec	Electron velocity
$\overline{v}_n$	cm/sec	Mean thermal velocity
γ		Number of electrons liberated by ion collision per ion
η_m		Mass efficiency
α		Condensation coefficient

DESIGN AND MECHANISM OF AN AUTOCATHODE

H. Bessling

1. Introduction /7*

In the ion source of a Kaufman thruster [1, 2, 3, 4], a plasma is generated by a gas discharge between an axial cathode and a cylindrical anode. From this plasma, with the aid of a strong electrical field, the thrust-generating ions are extracted through the boundary grid and accelerated. A magnetic field generated by an axial coil or magnetic rods causes the ionizing electrons in the discharge chamber to travel along trochoidal paths, so that the probability of collision is greatly increased by lengthening the path. An electron emitter neutralizes the ion beam. Of all the components of the thruster apart from the grids, the cathodes are subjected to the greatest loads due to intense erosion caused by the ions accelerated in the cathode fall.

Initially, filament cathodes were used in the Kaufman ion source, then simple oxide cathodes. The latter consist of a helical tungsten coil plated with an emitter having a low electron work function, usually barium or strontium oxide. The lifetime of these cathodes is drastically limited by ion bombardment, and is not sufficient for long space flight missions [5]. However, it should be mentioned that the development of oxide cathodes has not yet been concluded [6]. Longer operating times are obtained with the hollow cathode [7, 8, 9, 10] and the autocathode (liquid-metal cathode) [11].

* Numbers in the margin indicate pagination in the foreign text.

2. Design of the Experimental Facility

The autocathode under investigation is operated in a small discharge chamber located, together with the mercury feed system, in a 100-ℓ vacuum tank. The pressure in the tank can be reduced to $2 \cdot 10^{-4}$ torr using a Balzer diffusion pump Diff 3500 with a gas throughput of 1.5 tor ℓ/sec. Fig. 1 shows the entire experimental setup.

2.1. Discharge Chamber

The discharge chamber K_E schematically depicted in Fig. 2 consists of the V 2 A - steel cylinder Z, which is closed on one end by the flange F_1 bearing the autocathode K, and on the other /8
by two perforated discs L_1 and L_2. To determine the pressure in the discharge chamber, there is a Pirani vacuum-measuring tube, which is held by a pipe welded to the cathode flange. To investigated the effect of the magnetic field on the discharge, there is a magnetic-field coil M around the cylinder; it can be set to generate a flux density up to 200 gauss. In the cylinder itself, there is a ring-shaped anode A_n secured by porcelain insulators I_s. Anodes of varying diameter can be employed. The perforated discs L_1 and L_2 serve as a flow resistance, in order to keep the required pressure in the discharge chamber above 10^{-4} torr. If an electrical field is applied between the perforated discs by means of a high-voltage power supply, ions are extracted, thus making it possible to continuously vary the pressure in the discharge chamber within a small range without exchanging the perforated discs.

A T-tube is attached to the perforated discs of the discharge chamber. One arm of the T is sealed at the end by an inspection glass S, while the other contains a 15-cm Cheffron refrigerating baffle B_T to condense the Hg vapor leaving the chamber. The pumping rate S_B of the cryosurface A_B of this baffle is given by equation (2.1) in ℓ/sec:

$$S_B = 10^{-3} \frac{A_B}{4} \sqrt{\frac{8kT}{\pi m_{Hg}}} \alpha , \tag{2.1}$$

when A_B, T, and m_{Hg} are in units of cm^2, °K, and g, respectively. This gives $S_B \simeq 1900$ ℓ/sec for mercury, so that a vacuum of about $4 \cdot 10^{-5}$ torr can be created in front of the discharge chamber.

In order to be able to quickly detect disturbances in Hg intake, the cathode feedpipe is connected at its lower end to a glass capillary p. Because of capillary depression, which plays a role with small cross sections, the diameter of the capillary depends on the diameter of the cathode nozzle. Fig. 3 shows the photograph of the discharge chamber at the flange of the vacuum tank.

2.2. Feed System

With an engine thrust between 12 and 120 mN and a prescribed beam velocity of 30 km/sec, the Hg throughput is between 0.4 and 4 mg/sec, ocrresponding to an ion current of 0.2 to 2 A. A feed system [12] (Fig. 4) was designed for this throughput in /9
which mercury is pushed at a controlled rate through a porous tungsten disc with the aid of compressed gas. The Hg throughput is controlled by changing the compressed-gas pressure P_F. Fig. 5 shows mass throughput as a function of feed pressure for tungsten discs with porosities of 20, 30 and 40%. With the aid of this diagram, the desired mass throughput can be obtained by adjusting the value of the feed pressure.

2.3. Autocathode

Figs. 6 and 7 show the construction of a mercury autocathode for a Kaufman-thruster ion source. The cathode is attached, in an axial position, to the flange F_1 of the discharge chamber (Fig. 2). With the aid of the feed system F, the mercury goes through the channel K_{an} into the cylindrical hole H in the head of the cathode, which is sealed by replaceable molybdenum nozzles. Investigations with two types of molybdenum nozzles were conducted. The central holes of the first type (Nozzle I in Fig. 8) have different diameters, so that the free Hg surface facing the discharge in the lower region of the conical nozzle opening can be varied. The other type of nozzle (Nozzle II in Fig. 8) has a ring-shaped aperture, which is produced in a simple fashion by inserting a pin into the hole. With the aid of the cooling system K_{from}, K_{to}, the cathode temperature, and thus the temperature of the free Hg surface, can be adjusted to assigned values and varied within specified limits by changing the throughput of cooling water. Cooling is provided only for the studies. Later on, the operating temperature of the cathode can be set by appropriately arranged heat transfer from the cathode to the structure. The size and temperature of the Hg surface is important, since these values determine the pressure and mass throughput in the ion source. For this reason, a thermocouple is installed in the cathode head near the nozzle to measure cathode temperature. To ignite the discharge, argon can be fed through two 0.6-mm holes opening into the middle cathode aperture.

2.4. Ignition Mechanism /10

Igniting the gas discharge in a Kaufman ion source with an autocathode is considerably more difficult than with ion sources using other cathodes. In a Kaufman discharge with an oxide cathode, mercury vapor enters the discharge chamber and electrons are produced through the heating of the cathode even before ignition; thus, a relatively low voltage can be used for ignition. The situation is similar with a hollow cathode discharge. In this case, just 50 V was sufficient for ignition [10] after heating the electrode to 1230°C and introducing about $3 \cdot 10^{-3}$ g/sec mercury vapor into the discharge chamber. With a Kaufman source using an autocathode, there is no Hg intake until the liquid mercury carried to the cathode head is vaporized with the aid of the discharge current in the cathode nozzle. Before the beginning of operation, the chamber pressure is therefore very low, and no electrons are emitted either, so that ignition cannot be brought about by simple means. With the LM-cathode developed and described in [11], ignition is therefore brought about with the aid of a movable pin, as in an arc lamp, by touching and pulling apart the electrodes.

In order to avoid moving parts, with the cathode described here, the cathode head is heated to 300°C before ignition by a heating element, so that mercury evaporates into the chamber. The resulting buildup of Hg vapor pressure in the chamber is still not sufficient to permit ignition with relatively low voltages. Therefore, through two openings in the cathode head, argon was also fed in at a rate of about 1.5 torr ℓ/sec. Since even the minimum ignition voltage of argon (320 V) is lower than that of mercury (450 V), ignition was achieved with as little as about 700 V at the keeper in front of the cathode.

2.5. Electrical Circuit

Fig. 9 shows the electrical circuit of the experimental setup. The power supply U_M feeds a magnetic field coil M_S placed around the discharge chamber. With this coil, any desired magnetic flux density (axial) at the end of the coil up to about 200 gauss can be created. The power supply U_E delivers the discharge voltage; the power supply U_Z employed for ignition can be switched over with the aid of the switch S_u to increase the discharge current from the keeper to the discharge gap.

3. Function of the Autocathode

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With this autocathode, liquid mercury is carried with the aid of a feed system [12] to the cathode head located in the discharge chamber, and there, in a conical nozzle, forms a free surface facing the discharge with an area of about 10^{-2} to 10^{-1} mm^2. During operation, the base of the cathode site of the gas discharge is on this mercury surface, so that mercury evaporates into the discharge chamber in accordance with the evaporation curve. The evaporation rate m' in $g/sec/cm^2$ is a function of temperature, as given in equation (3.1), and holds only for evaporation into vacuum.

$$m' = \sqrt{\frac{m_o M}{2\pi kT}}\, P_s \qquad (3.1)$$

The resulting equation for mercury is

$$m'_{Hg} = 5{,}85 \cdot 10^{-2}\sqrt{\frac{M_{Hg}}{T}}\, P_s \qquad (3.2)$$

in $g/sec/cm^2$, where M_{Hg} is the atomic weight and T and P_s are expressed in °K and torr, respectively.

In accordance with equation (3.3), the saturation vapor pressure P_s has a rapid rise approaching that of an exponential function:

$$P_s = C\, e^{-\frac{q_o}{RT}}\, T^{\frac{c_p - c_{fl}}{R}} . \qquad (3.3)$$

The size and temperature of the mercury surface must now be chosen so that the evaporation of mercury from it corresponds to the mass throughput of the feed system required in accordance with equation (3.4):

$$F = \dot{m}_F \, v_a \, , \tag{3.4}$$

to obtain the required thrust F with a given beam velocity v_a. The relationship between Hg surface area A_K and temperature T in the nozzle, beam velocity, fuel efficiency η_m, and thrust F can now be derived from equations(3.1), (3.3), and (3.4):

$$A_K = \frac{F \sqrt{2\pi k T}}{\sqrt{m_{Hg}} \; v_a \eta_m \, C \, e^{\frac{-q_o}{RT}} \, T^{\frac{C_p - C_{fl}}{R}}} \tag{3.5}$$

The relationship depicted in Fig. 10 between Hg throughput /12 $\dot{m}_{Hg}$, the diameter d_k of the evaporating Hg surface and the cathode temperature can be calculated from equation (3.2). The feed pressure p_F required for a desired throughput can be read off a throughput characteristic of the feed system in Fig. 5. For a uniform gas discharge, it is necessary, among other things, that in the event of disturbances of the equilibrium position of the mercury in the cathode nozzle, stabilization is automatically achieved as soon as possible. As later became evident, this requirement can be satisfied to only a limited extent by using a conical nozzle. If, for instance, with constant Hg intake, a disturbance appears in the Hg equilibrium position in the nozzle due to an increase in the discharge current, the temperature of the cathode will rise, and, hence, so will the mercury evaporation rate. The mercury level in the nozzle drops. However, now a new mercury equilibrium position is automatically achieved, since, because of the smaller Hg surface, the evaporation rate and thus the discharge current as well become smaller again. Both experiments and a computational analysis showed, however, that this automatic process is not sufficient to guarantee undisturbed continuous operation of the thruster over long periods of time. Therefore, an external control system must be employed.

The destruction of a cathode is primarily due to evaporation of cathode material and erosion as a result of bombardment by the ions accelerated in the cathode fall. Since the Hg surface exposed to ion bombardment is constantly renewed by a continuous flow of mercury, these causes of cathode destruction are, within certain limits, eliminated. Erosion phenomena turned up in the experiments at the cathode nozzle. The extent to which this erosion is tolerable must be determined by a long-term test.

4. Cathode Mechanism

To investigate the nature of electron emission at the cathode, the following mechanisms were considered: thermal electron emission, electron liberation due to ion collision, and field emission.

4.1. Thermal Electron Emission /13

The current density of thermal electron emission is obtained from the Richardson equation in A/cm^2 (with T in °K):

$$j_{eT} = 120\, T^2\, e^{-\frac{eU}{kT}} \tag{4.1}$$

With the electron work function eU = 4.53 eV for mercury, and a cathode temperature of about 400 K to 600 K, equation (4.1) yields current density values of a magnitude which can be neglected.

4.2. Electron Liberation Due to Ion Impact

There are no experimental results on the number of electrons knocked out by Hg ions accelerated in the cathode fall bombarding a mercury surface. However, Fig. 11 shows the dependence of the ratio

$$\gamma = \frac{n_e}{n_i} = \frac{\text{number of expelled electrons}}{\text{number of impacting ions}}$$

on ion energy for the bombardment of various substances by a number of other types of ions listed in Table I [13]. It can be seen that the value of γ depends very strongly on the kinetic energy of the ions and does not exceed the value 1 until 1.5 to 2 keV.

Using the energy balance for the cathode surface, Compton [14] studied the ratio of electron and ion current densities for an Hg discharge in vacuum and found the value $j_e/j_i = 4.65$. Since $j_e/j_i = n_e/n_i$, this ratio also furnishes the number of emitted electrons and impacting ions. The ion energy at the autocathode is about 20 eV. The values of γ for the substances included in Fig. 11 are already less than 10^{-2} for 100 eV. Assuming similar behavior for ion bombardment of the autocathode, the contribution of ejected electrons to the total emission current can likewise be neglected.

4.3. Electron Field Emission /14

Fowler and Nordheim [15] and, particularly, Wasserrab [16] have made studies of electron field emission in gas discharges with evaporating cathodes, and the following investigations will be based on their results.

In our autocathode model, we will assume that there is a sharp phase boundary between liquid mercury and mercury vapor in the conical cathode nozzle at the cathode foot of the discharge. This model does not reflect the true situation. Since the physical state in the liquid-vapor transition region has not yet been adequately established, the numerical results of this consideration are significant only with respect to orders of magnitude.

TABLE I (FOR FIG. 11)

Designation of the curve in Fig. 11	Impacting ion	Target material
a	H_1 and Na	Cu
b	K	Al
c	Li	Al
d	Rb	Al
e	H_1	Cu,Al,Au
f	H_1	Ni
g	Rb	Ag Mg
h	Li	Ag Mg
i	H^-	Ag Mg
K	A	Ni Cr V

Several free path lenths from the Hg surface in the cathode nozzle, there is an ionization region with a very strongly contracted plasma, from which ions flow toward the cathode and electrons into the positive column. Cathode spot current density measurements of Froome [17] yielded values greater than 10^6 A/cm^2. With the aid of the Langmuir $U^{3/2}$ equation, it could be shown [16] that such great densities for pure ion currents are possible only at field strengths at which electron field emission will already appear. The cathode spot current must therefore be ambipolar. /15

To determine the electrical field strength in front of the cathode, the Mackeown equation for the ambipolar current [16, 18, 19]:

$$E^2 = 7.56 \cdot 10^5 \left(j_i \sqrt{\frac{m_i}{m_e}} - j_e\right)\sqrt{U_k}, \tag{4.2}$$

is combined with the Fowler-Nordheim equation for electron field emission [15, 18] (eU = electron work function):

$$j_e = j_{eF} = 1.54 \cdot 10^{-6} \frac{E^2}{U} e^{-\frac{6.83 \cdot 10^7 U^{3/2}}{E}} f(g) \tag{4.3}$$

$$g = \frac{3.79}{U} \cdot 10^{-4} \sqrt{E}, \tag{4.3a}$$

$$f(g) \approx 1 - g, \tag{4.3b}$$

and thus the field strength is obtained as a function of the ratio j_i/j_e.

$$E = \frac{10^8}{(\ln N)^2} \left(\sqrt{3.25\, U + 0.955\, U^{3/2} \ln N} - 1.76 \sqrt{U}\right)^2 \tag{4.4}$$

$$N = \frac{\sqrt{U_K}}{U}\, 1.16\, (610\, j_i/j_e - 1). \tag{4.4a}$$

According to Compton [14], the ratio j_e/j_i can be estimated with the aid of an energy balance for the cathode surface.

$$\frac{j_e}{j_i} = 4.65 . \tag{4.5}$$

This value is substituted in the field-strength equation (4.4), so that E can now be determined numerically.

The ion bombardment and the radiation from the contracted plasma of the ionization region heat the mercury surface at the cathode head so that Hg evaporates and flows into the ionization region. The velocity v_n of the neutral Hg atoms at the mercury temperature T_o is: /16

$$\bar{v}_n = \sqrt{\frac{8k\,T_o}{\pi m_{Hg}}}, \qquad (4.6)$$

For the cathode potential fall U_K, the electron velocity is:

$$v_e = \sqrt{\frac{2eU_K}{m_e}} \qquad (4.7)$$

If the mercury temperature at the base of the discharge is about 2000 K and the cathode potential fall is about 20 V, the ratio v_e/v_n has the value $1.5 \cdot 10^3$. Hence, the electrons can ionize the mercury vapor (ionization potential 10.4 V) by collisions. With a special experimental setup, Kobel [20] found the evaporation rate of mercury in the vicinity of the cathode end of the discharge as a function of discharge current:

$$\frac{\dot{m}_{oHg}}{I_g} = 1.7 \cdot 10^{-5}\ [\mathrm{g/sec/A}] \qquad (4.8)$$

With this setup, evaporation outside the base of the discharge was prevented to a great degree by cooling the cathode. In that case, the evaporating mercury will be that part which is not ionized in the ionization region and which therefore does not return to the cathode as ion current. The ratio of Hg ion throughput and neutral particle throughput $\dot{m}_{iHg}/\dot{m}_{oHg}$ can then be expressed as a function of the ratio j_e/j_i:

$$\frac{\dot{m}_{iHg}}{\dot{m}_{oHg}} = \frac{I_i}{e} \frac{m_{Hg}}{1.7 \cdot 10^{-5} I_g} = \frac{122.7}{(1+\frac{j_e}{j_i})} \qquad (4.9)$$

It has the value

$$\frac{\dot{m}_{iHg}}{\dot{m}_{oHg}} = 21.6 \quad , \qquad (4.10)$$

i.e., about 96% of the mercury evaporated from the cathode end of the discharge is ionized. The mercury ions formed by electron collision are accelerated in the cathode fall, bombard the cathode surface, surrender their charge, and heat up the electrode. The neutral particles diffuse into the discharge chamber. /17

The total cathode spot current density

$$j = j_e + j_i, \qquad (4.11)$$

can be calculated from the combination of equations (4.2), (4.5) and (4.11)

$$j = \frac{E^2 \left(\frac{j_i}{j_e} + 1\right) \cdot 10^{-5}}{7.56\sqrt{U_K}\left(\frac{j_i}{j_e}\sqrt{\frac{m_i}{m_e}} - 1\right)} . \qquad (4.12)$$

The components of ion and electron current densities and currents and the diameter of the cathode spot current are

$$j_{i,e} = j \frac{1}{1 + \frac{j_{e,i}}{j_{i,e}}} \quad , \qquad (4.13)$$

$$I_{i,e} = I \frac{1}{1 + \frac{j_{e,i}}{j_{i,e}}} , \tag{4.14}$$

$$2r_K = 2 \sqrt{\frac{J}{j\pi}} . \tag{4.15}$$

The flow rates of the mercury ions and neutral particles at the cathode spot are:

$$\dot{m}_{iK} = \frac{J}{(1+ \frac{j_e}{j_i})} \frac{m_{Hg}}{e} , \tag{4.16}$$

$$\dot{m}_{oK} = 1.7 \cdot 10^{-5} J . \tag{4.8}$$

The total throughput at the cathode focal spot is then /18

$$\dot{m}_K = J \left(\frac{m_{Hg}}{e(1+ \frac{j_e}{j_i})} + 1.7 \cdot 10^{-5}\right). \tag{4.17}$$

In equations (4.2) to (4.17), field strength E is in V/cm, the voltages U_K and U in V, the current densities j_i and j_e in A/cm^2, and the elementary charge e in A·sec.

In summary, the model in 4.3 yields the following cathode mechanism:

1. At the cathode end of the discharge, electrons leave the mercury surface due to field emission.

2. These electrons accelerated in the cathode fall ionize almost completely the mercury vapor rising due to the high temperature at the cathode base of the discharge.

3. Between the ionization region and the cathode surface, there is formed an ambipolar current, which generates in front of the cathode a field intensity sufficient to induce field emission.

4. The mercury ions accelerated in the cathode fall region bombard the cathode, transfer their kinetic energy to the cathode as heat, so that further Hg can evaporate and lose their charge.

5. The nonionized mercury atoms diffuse into the vacuum.

6. The electrons from the ionization region move toward the anode along the field lines.

5. Performance Data and Numerical Analysis /19

Some performance data for liquid-metal cathodes with various cathode-nozzle configurations are collected in the following table.

Fig. 12 depicts the current-voltage characteristic for Nozzle III. Fig. 13 shows the anode current for Nozzle II recorded over a period of time with a Siemens printer. At point t_a, the power supply in parallel, which had been employed for ignition, was withdrawn, and the anode current supply switched in. This switching process is the reason for the brief current drop visible at this point in the diagram.

The numerical analysis of this cathode model for a discharge current of 6 A gave the values listed in Table III. With the aid of these figures, questions on the design of the cathode can be answered; e.g. on the diameter of the free mercury surface and thus the size of the hole in the cathode. In order to achieve a good electrical efficiency, the cathode must be operational at relatively high temperatures. At these temperatures, however, the mercury evaporation rate per unit area is very large. /20
However, the quantity of mercury evaporating from the cathode,

TABLE II

Nozzle		I	II	III
Duct diameter	mm	0.25	0.22	0.25
Diameter of inserted pin	mm	-	0.14	0.125
Vertex of angle of cone	degrees	30	30	30
Magnetic field coil current	A	6	4	6
Hg feed pressure	kg/cm^2	5.5	4.75	5.8
Hg feed throughput	g/sec	$8 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$
Ignition voltage	V	800	800	800
Cathode temperature	°C	225	180	185
Discharge current	A	10	5	4...10
Discharge voltage	V	15	17	22...15

which is determined by the thrust, and thus by the size of the ion beam, depends not only on temperature, but also naturally on the size of the free mercury surface, i.e. on the diameter of the cathode hole. This diameter must then be kept very small, so that the mercury evaporation does not exceed the prescribed value.

With reference to the electrical discharge mechanism, the lower limit of the diameter of the free mercury surface is a function of the diameter of the current paths, the value of which can be obtained from Table III. In order to push the mercury through this narrow channel, however, a pressure on the order of about 100 kg/cm^2 is required, in accordance with Hagen-Poiseuille:

$$\dot{m} = \frac{\rho \pi r_K^4}{8\eta(T) l} p_F ,$$

Hence, the diameter of the hole is also determined by data from fluid mechanics.

TABLE III

E	$= 6.5$	$\cdot\ 10^{7}$	V/cm	Electrical field strength
j_i	$= 0.31$	$\cdot\ 10^{7}$	A/cm^2	Ion current density
j_e	$= 1.43$	$\cdot\ 10^{7}$	A/cm^2	Electron current density
j	$= 1.74$	$\cdot\ 10^{7}$	A/cm^2	Total current density
$2r_K$	$= 6.6$	$\cdot\ 10^{-3}$	mm	Diameter of a current path
I_i	$= 1$		A	Ion current
I_e	$= 5$		A	Electron current
I_{nk}	$= 0.048$		A	Equivalent current of the neutral particles at the cathode focal spot
$\dot{m}_{ik}$	$= 2.2$	$\cdot\ 10^{-3}$	g/sec	Ion throughput at the cathode focal spot
$\dot{m}_{nk}$	$= 0.1$	$\cdot\ 10^{-3}$	g/sec	Neutral particle throughput at the cathode focal spot
m'_{nk}	$= 290$		g/sec/cm^2	Neutral particle throughput density at the cathode focal spot

Of the mercury evaporating from the cathode focal spot, /21
$2.2 \cdot 10^{-3}$ g/sec is ionized (Table III). Because of their positive charge, these Hg ions return to the cathode in the electrical field of the cathode fall, lose their charge and can again be evaporated. Only 10^{-4} g/sec mercury enters the anode volume as neutral particles. With a total mass throughput at the cathode of

about $4 \cdot 10^{-3}$ g/sec Hg, which is required for an ion current of 2 A, it is thus justified to determine the Hg evaporation rate as in Section 3 from equation (3.1), in agreement with the experiment. This is true only as long as the free mercury surface is large relative to the cross section of a discharge current path, since the evaporation rate at the base of the focal spot is locally about 290 g/sec/cm^2 according to Table III, while at a temperature corresponding to the cathode of e.g. 300°C, only 10 g/sec/cm^2 mercury evaporates, in accordance with equation (3.1). With a cathode hole of up to roughly 0.1 mm, the above condition can be considered satisfied.

6. Summary /22

For gas discharge ion sources with long operating times, two types of cathodes come into consideration: the hollow cathode and the autocathode. In order to test and develop an autocathode, a test setup was designed with a 100-ℓ vacuum chamber and the required energy supply. As opposed to previously known arrangements, the discharge is ignited after feeding in argon as an auxiliary gas through the cathode. Because of the increase in chamber pressure and the lower ignition voltage of argon, the ignition required substantially lower voltages.

Thermal emission, electron liberation due to ion collision, and field emission were considered as possible explanations of the cathode mechanism of the autocathode. Thermal emission and ion collision are of subordinate importance, and the release of electrons takes place almost entirely through field emission. Based on a model, order-of-magnitude values were calculated at a given discharge current for, among other things, field strength in front of the cathode, electron and ion current densities, and neutral particle throughput, values which can be utilized in the design of the cathode.

Performance data and discharge characteristics were recorded for various cathode-nozzle configurations.

List of Figures and Diagrams

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